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DOES WRINKLE RIDGE FORMATION ON MARS INVOLVE MOST OF THE LITHOSPHERE?;

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Recent work on the origin of wrinkle ridges suggests that they are compressional tectonic features whose subsurface structure is not understood. In this abstract, we briefly review some characteristics of Martian wrinkle ridges which suggest that they are the surface expression of thrust faults that extend through much of the lithosphere.

Photoclinometric profiles across wrinkle ridges in Lunae Planum show an average regional elevation offset across the ridges (plains on one side of the ridge are at a distinctly different elevation than plains on the other) of about 100 m. The offset in regional elevation extends for many kilometers on either side of the ridge and suggests a fault beneath the structure; simple fold structures or faults that flatten into a decollement do not readily explain the elevation offset. A combination of folding and thrust faulting, however, can produce both the observed ridge morphology and the offset in regional elevation. The lateral extent of the regional elevation change requires a planar fault that does not shallow with depth, because the regional elevation change would decrease to zero above the point where the fault flattens to a decollement (1).

A number of attempts have been made to identify kinematic models capable of explaining the salient characteristics of wrinkle ridges. In particular, fault-bend and fault-propagation folding have been suggested as possible models for the development of wrinkle ridges (2, 3). Fault-bend folding (4) can produce an anticlinal fold when surficial rocks are translated over a surface-flattening bend in a thrust fault. Fault-propagation folding (5, 6, 7) occurs when displacement along a reverse fault at depth is accommodated by folding of overlying layers. Both types of structures are capable of producing surface folds with complex near surface faulting, similar to wrinkle ridges. More detailed considerations suggest, however, that the gross structure of wrinkle ridges is different from typical fault-bend and fault-propagation folds. In particular, faults responsible for both fault-bend and fault-propagation folds most commonly shallow out into horizontal decollements at bedding-plane contacts between rocks with distinct mechanical properties. In addition, where observed on the earth, the step-up ramps associated with these types of structures are sharp, rather than gradual, making a gradually changing fault dip (for example a thrust fault gradually shallowing with depth) unlikely. If the fault dip shallowed or completely flattened with depth, the offset in regional elevation would also decrease or disappear and abrupt changes in fault dip would produce correspondingly abrupt changes in surface elevation away from wrinkle ridges. Furthermore, the shortening across wrinkle ridges is small (hundreds of meters; 1), much less than that likely by formation of these structures by fault-bend or fault-propagation folding. For these types of folds, the long rear limb of the fold is produced by translation of rocks above the thrust ramp. This in turn requires that the slip across the structure be roughly equal to the width of the rear limb. The rear limb of most wrinkle ridges is many kilometers wide, which is an order of magnitude greater than the shortening that can be reasonably accommodated across them (1). Thus, the lack of evidence for horizontal decollements beneath wrinkle ridges and the excessive strains suggested for fault-bend and fault-propagation folds suggest that a different deep subsurface structure might be more applicable for the overall geometry of planetary wrinkle ridges, although fault-bend and fault-propagation folding could still be responsible for near-surface folding and faulting.

In northwestern Lunae Planum wrinkle ridges are spaced about 50 km apart and consistently have an uplifted eastern side. The regional elevation change appears to persist laterally for many kilometers away from the ridges. There is no evidence for tilted blocks between the ridges (dips of 1° or greater would have been detected), and no evidence for any folding or warping of the surface between the ridges. To first approximation, the faults beneath these ridges must dip to the east, to produce the uplifted eastern side, and continue at least 50 km to the next ridge. If the fault dips at roughly 25°, then the fault is roughly 25 km beneath the surface at this distance. Steeper dips would result in greater depths of penetration; a 45° dipping fault would be at

50 km depth beneath the adjacent ridge. Note that even if the surface between adjacent wrinkle ridges was tilted at less than a degree, the underlying fault must still continue laterally to the next ridge, at which point it would probably be tens of kilometers below the surface (e.g., 8). This suggests that the faults responsible for wrinkle ridges clearly involve a significant thickness of the Martian lithosphere and are not simply surface folds affecting the upper few kilometers of the crust.

There is strong evidence that faults beneath foreland basement uplifts, such as the Rocky Mountains, are underlain by planar faults that root in the weak ductile lower crust near the Moho. Best known of these basement thrusts is the Wind River thrust (9), which dips about 40°, has slipped about 5-7 km, and is clearly imaged on seismic profiles to about 20 km depth. Geometric considerations indicate the fault zone flattens near the Moho at about 35 km depth. Numerous other basement thrusts have been documented in the Rocky Mountain foreland and elsewhere worldwide in the course of petroleum exploration (e.g., 10, 11). Many of these basement thrusts have small offsets on the order of hundreds of meters and have a change in elevation across the structure similar to wrinkle ridges. Some of the best documented examples are in the Wind River basin (11). The deformation is entirely by fault slip in the basement, but as the fault enters the 1-3 km thick sedimentary cover, fault-bend folding, wedging and fault-propagation folding produce structures that are quantitatively similar to the kilometer-scale aspects of wrinkle ridges.

On Mars, a number of supporting arguments and models also permit the rooting of faults responsible for wrinkle ridges in a weak ductile lower crust or lithosphere. The flexure of volcanic loads on the Martian surface (12) and the magma source region required beneath the giant Tharsis volcanoes (13, 14) both suggest a lithosphere on the order of 50 km thick at the period in Tharsis history when wrinkle ridges formed. Assuming a 50 km thick lithosphere, with a basaltic crust 30 km (15) to 100 km thick (16, 17, 18) and an olivine mantle (19, 20), requires thermal gradients of 9°/km to 16°/km from ductile creep properties of basalt and olivine. Thermal evolution models of Mars (21) also predict a present average crustal thermal gradient of 9°/km, which is a likely minimum as thermal gradients were undoubtedly greater during Tharsis volcanic and tectonic activity. Given these constraints, we have assumed 9°/km, 15°/km, and 20°/km and various crustal thicknesses for the construction of lithospheric strength envelopes (brittle and ductile yield stress versus depth curves) to gain a better understanding of likely lithospheric strong and weak zones at depth.

Results show that even under the coolest conditions a lower crustal weak zone is present below 40 km, assuming a minimum 50 km thick crust. Under the warmer conditions more likely for Tharsis, lower crustal weak zones begin at about 20 km depth, with all strength in the upper mantle gone at 40-60 km depth. These calculations indicate that under conditions likely during Tharsis deformation, weak zones at fairly shallow depths existed within the crust and mantle in which thrust faults could root, analogous to faults beneath foreland basement uplifts on the earth. These results suggest a mechanism that links wrinkle ridge formation with much of the lithosphere.

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